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DESIGN, PERFORMANCE, AND TEST EXPERIENCE OF FOUR MULTIHUNDRED-KILOWATT-ELECTRIC HEAT SOURCES FOR LIQUID-METAL SYSTEMS

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by Henry B. Block, Lawrence A. Mueller, and Fred Boecker, Jr.

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

Four different electric heaters were designed to supply the energy required for a SNAP-8 space-power-system test. Two heaters were compact units designed to physically simulate the SNAP-8 reactor thermal-dynamics. The remaining two heaters were heavy-duty units designed primarily to provide highly reliable heat sources. Heater design power was 350 kWt for the first two units constructed and 600 kWt for the last two units constructed. Heater inlet temperature was 1100° F (865 K); discharge temperature was maintained at 1300° F (977 K). Total operational time to date on all four heaters is about 4400 hours. The compact heaters had operational problems and were replaced prior to the completion of their respective tests. Experience with the compact heaters improved the heavy-duty heaters' final design. The heavy-duty heaters were used during most of the testing and were considered successful.

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DESIGN, PERFORMANCE, AND TEST EXPERIENCE OF FOUR MULTIHUNDRED-KILOWATT-ELECTRIC HEAT SOURCES FOR LIQUID-METAL SYSTEMS

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SUMMARY

Four different electric heaters were designed to supply the energy required for the SNAP-8 space-power-system being tested at Lewis. Such heaters are important for use in development of reactor power systems, such as SNAP-8, because testing with a reactor is difficult, time consuming, and expensive. Two of these heaters were compact units which were designed to physically simulate the SNAP-8 reactor thermal-dynamics. The remaining two heaters were heavy-duty units designed primarily to provide highly reliable heat sources. The heavy-duty heaters weighed at least twice as much as the compact heaters.

Heater design power was 350 kilowatts-thermal for the first two units and 600 kilowatts thermal for the last two units. Heater inlet temperature was 1100° F (865 K), and discharge temperature was maintained at 1300° F (977 K).

Total operational time to date on all four heaters is about 4400 hours. The compact heaters had operational problems early in their lives and had to be replaced prior to the completion of their respective tests. However, most of the design problems became evident with these compact heaters and the final design of the heavy-duty heaters was such that these problems were limited. The heavy-duty heaters were used during most of the testing and were considered quite successful.

The problems encountered are discussed, and the solutions found and proposed are described.

INTRODUCTION

A SNAP-8 mercury Rankine cycle electrical generating system was tested at Lewis (ref. 1). The SNAP-8 system consists of three major liquid-metal subsystems: the primary or heat-source subsystem, which utilizes a eutectic mixture of sodium-potassium

(NaK-78) as the heat-transfer medium (ref. 2); the power subsystem, which uses mercury as the working fluid; and the heat-rejection subsystem, which uses NaK to remove waste energy from the power subsystem. In the flight system, a nuclear reactor will supply energy to the primary subsystem. Since testing with a reactor is difficult, time consuming, and expensive, an electric heat source and its controls were substituted for the reactor (ref. 3). The electric heat source's major function was to reliably supply energy to the primary subsystem; the secondary function was to simulate the reactor's transient characteristics.

Four electric heaters were designed, built, and utilized in a series of SNAP-8 system tests at Lewis. Two heaters were made compact in order to produce a moderately close physical simulation of the thermal-dynamic characteristics of the reactor. The remaining two heaters were designed primarily for high reliability and were much larger than the compact heaters.

These electric heaters basically consist of sheathed heating elements immersed in the NaK fluid; each heater element bundle is contained within a metallic vessel. The fluid enters the bottom of the container, passes over the heating elements, and exits at the upper heater surface.

Heaters constructed early in the program were designed for an inlet temperature of 1100° F (865 K), a 1300° F (977 K) discharge temperature, a flow of 34 500 pounds mass per hour (4.34 kg/sec), and a normal operating power of about 350 kilowatts-thermal. Later heaters operated in the same temperature range, but were upgraded to a new flow of 45 000 pounds mass per hour (5.65 kg/sec) and an operating power of about 600 kilowatts-thermal. Listed in the following table are the heaters in the order in which they were tested, along with several general characteristics for each heater:

Heater	Rated power, kWt	Number of elements	Heat-flux density at rated power		Weight	
			$W/in.^2$	W/cm^2	lbm	kg
Compact heater 1	350	162	68.0	10.6	600	270
Heavy-duty heater 1	350	192	26.0	4.03	1250	567
Compact heater 2	600	144	117.0	18.25	380	172
Heavy-duty heater 2	600	204 (192 used)	34.0	5.28	1200	544

Although these heaters were designed for the SNAP-8 system, they can be used in other liquid-metal systems operating over a wide range of temperatures and flows.

This report presents the design and performance of these four heaters and describes the test experience with these heaters. Design criteria and thermal and mechanical design are discussed. Heater internal hot-spot temperature, internal temperature distribution, pressure drop, efficiency, and test experience are presented in detail for each heater.

For clarity and brevity in presentation, thermal power in kilowatts is expressed as kWt, and electric power output in kilowatts from the complete power system is expressed as kWe.

SYMBOLS

A	heat-exchanger total heat-transfer area, ft^2; m^2
A_c	heat-exchanger minimum free-flow area, ft^2; m^2
c_p	NaK specific heat at constant pressure, Btu/(lbm)(^oF); J/(kg)(K)
f	mean friction factor
G	ratio of NaK mass flow to open area
g_c	conversion factor, (ft)(lbm)/(lbf)(sec^2); (m)(kg)/(N)(sec^2)
h	average heat-transfer coefficient, Btu/(hr)(ft^2)(^oF); W/(m^2)(K)
K_c	contraction loss coefficient for flow at heat-exchanger entrance
K_e	contraction loss coefficient for flow at heat-exchanger exit
k	NaK thermal conductivity, Btu/(hr)(ft^2)(^oF)/ft; W/(m)(K)
M	NaK mass flow rate, lbm/hr; kg/sec
P	pressure, psi; N/cm^2
Q_{reqd}	system required energy flux, Btu/hr; J/hr
T	temperature, ^oF; K
T_{lm}	log mean temperature difference, ^oF; K
v_1	inlet specific volume, ft^3/lbm; m^3/kg
v_2	outlet specific volume, ft^3/lbm; m^3/kg
v_m	mean specific volume, ft^3/lbm; m^3/kg
Δ	change from reference value
μ	dynamic viscosity, lbm/(ft)(sec); kg/(m)(sec)
σ	ratio of free-flow area to frontal area

DESIGN CRITERIA

In order to simulate the SNAP-8 reactor, the reactor's characteristics were broken into three functions: reactor control system, reactor nucleonics, and reactor thermal-dynamics. The simulation method selected consisted of analytical representations of the reactor nucleonics and control-drum logic and a physical representation of the reactor thermodynamics. The electric heater and its ignitron controller were controlled by an analog computer in order to simulate all three functions of the reactor.

Compact Heaters

The compact heaters' design criteria were to closely duplicate the total heat capacity, flow distribution, and flow passages of the reactor. The reactor's physical characteristics are presented in table I and figure 1. Exact duplication of the reactor core geometry was very difficult because the core itself was extremely compact. Another consideration was that both heaters were to be designed with some margin. A reserve capability was built into the heaters so that the failure of several individual heater elements would not cause general overheating. Data from the heater-element manufacturer (ref. 4) indicated that for long life, the element wire temperature should be maintained below 1600° F (1143 K) and be subjected to a minimum number of heat-cool cycles.

When compact heater 1 was designed, a reactor simulator capable of a maximum 400 kWt, with a 1300° F (977 K) discharge temperature, at a NaK flow of 34 500 pounds mass per hour (4.34 kg/sec) was required. Pressure drop was important but not critical.

Several years later when compact heater 2 was designed, the SNAP-8 system requirements had changed. This heater had a required capability of 600 kWt, and 1300° F (977 K) discharge temperature at 45 000 pounds mass per hour (5.65 kg/sec) NaK flow rate. In order to lower the heater-wire operating temperature substantially below the maximum allowable operating value, the heater-element design was modified to give good heat transfer from the heater wire to the NaK stream. Heater pressure drop was limited to 7 psi (4.8 N/cm^2) at maximum flow. The second compact heater also would utilize all additional technology developed for the previous heater designs.

Heavy-Duty Heaters

The primary consideration was to provide highly reliable heaters that would meet the energy requirements of the SNAP-8 system. Also, the heaters were to be relatively simple to construct, and compact enough to fit into the allotted area of the test facility. Length and number of heater cartridges were increased to effect a decrease in heat-flux density.

Heavy-duty heater 1 was designed to provide a maximum of 550 kWt at 1300° F (977 K) NaK discharge temperature, and 34 500 pounds mass per hour (4.34 kg/sec).

Heavy-duty heater 2 has an 800 kWt maximum power capacity at 1300° F (977 K) discharge temperature and 45 000 pounds mass per hour (5.65 kg/sec). Pressure drop was limited to no more than 7 psi (4.8 N/cm^2). As with compact heater 2, the heater-element design was modified to increase its heat-transfer coefficient. The objective again was to lower the heater-wire operating temperature. This heater was different from all the others because heater-element spacing was radially increased, flow was baffled in a serpentine manner, and 12 spare heater elements were built into the unit.

A final design criterion for all the heaters was that they would be compatible with the existing wiring and power supply.

HEATER DESCRIPTION

Two basic heater types were designed, fabricated, and tested: the compact heaters (reactor simulators) and the heavy-duty heaters. Each heater is described in the chronological order of design. Table II presents a listing of the characteristics of the four heaters. The power rating of the heater elements used in the various heaters was varied by changing wire diameter and length.

Compact Heater 1

This heater was designed to closely duplicate the physical dimensions and the heat-flux density of the SNAP-8 reactor. At 350 kWt, the heat-flux density of this heater was 68 watts per square inch (10.6 W/cm^2) compared with 61 watts per square inch (9.5 W/cm^2) for the reactor. Compact heater 1 (fig. 2) weighed 600 pounds mass (270 kg), was 25 inches (64 cm) long, had a hexagonal cross-sectional dimension of 12 inches (31 cm) flat to flat, and contained 162 heater elements (cartridges).

The electric heater cartridges were placed inside tubular wells which were welded to the upper bulkhead. To improve heat transfer, the gap between the heater elements and the heater wells was filled with helium. Spacer rods were installed around the heater wells to form annular passages which approximated the available flow area in the reactor. NaK entered the inlet plenum, from which it was distributed to channels paralleling the heater wells by a pattern of drilled holes in the flow-distribution plate. Longitudinal flow occurred in the spaces between the heater wells and the spacer rods. These rods extended from the lower end of the heater wells to within 2.5 inches (6.4 cm) of the upper bulkhead. NaK flowed laterally in the upper bulkhead region through the open passages between heater wells, into the surrounding manifold, to the outlet port.

Stay rods and reinforcing plates were used to strengthen the containment vessel. This heater was constructed of 316 stainless steel - with the exception of the heater-cartridge sheaths, which were Inconel.

Figure 3 presents a sectional view of the Watlow Company heater cartridge used in compact heater 1. Each cartridge was 21 inches (53.4 cm) long, had a heated length of 16.5 inches (41.9 cm), and was capable of producing 3.2 kWt. Nickel power leads, located in the center of the cartridge, were insulated by small magnesium oxide (MgO) ceramic cylinders. Nichrome heater wire was wrapped around each of the cylinders and connected to the nickel power leads. A 0.030-inch (0.076-cm) layer of powdered magnesium oxide insulated the heater wire from the Inconel sheath (which was at ground potential). The unheated ceramic portion reduced the chance of overheating in this upper NaK discharge region, and a lava end seal served as a moisture barrier.

The thermal conductivity of the ceramic material located between the heater wire and the Inconel wall, for the most part, determined the operating temperature of the heater wire. This thickness of MgO caused about a 125° F (71 K) temperature drop from the heater wire to the heater wall.

Heavy-Duty Heater 1

Heavy-duty heater 1 was designed with 192 heating cartridges, each 40 inches (102 cm) long. This resulted in a drop in surface-power density to 26 watts per square inch (4.03 W/cm^2), about one-half that of compact heater 1, and an anticipated 50° F (28 K) drop in heater-wire operating temperature. For this increased heater reliability, the penalty was an increase in size and weight of the heater. This heater, shown in figure 4, weighed 1250 pounds mass (570 kg), was 44 inches (112 cm) long, and had a diameter of 14 inches (36 cm). For ease of fabrication, this heater's containment vessel was cylindrical. An additional flow-distribution plate was installed to assure proper flow from the large lower plenum.

As in the first compact heater, heater cartridges were placed in tubular wells and spacer rods were incorporated to form annular passages for the NaK fluid. Because of the close fit between the heater cartridges and the heater wells (after heat up) experienced in compact heater 1, it was decided not to use helium to fill whatever voids remained between the two parts in this heater. Liquid metal entered the bottom of the heater, was distributed to the individual passages, flowed longitudinally between the heater wells and spacer rods, and exited through the top port.

Heater cartridges installed in this heater were similar to those used in compact heater 1, with two exceptions (fig. 5): the total length was increased to 40 inches

(102 cm) with a heated length of 36.7 inches (93.4 cm), and provision was made for temperature measurement within 12 heaters.

Compact Heater 2

Compact heater 2 was designed to have a maximum operating heater power of 675 kWt. This electric heater weighed 380 pounds mass (172 kg), was 22.5 inches (57.1 cm) long, 12 inches (31 cm) in diameter, and contained 144 heater cartridges (fig. 6). At 600 kWt, the heat-flux density of this heater was 117 watts per square inch (18.1 W/cm^2); it was constructed entirely of 316 stainless steel.

A new type of heater cartridge was designed for this heater to offset the increased heat-flux density and to achieve a lower heat capacity (fig. 7). The heater-element wall was increased to 0.110 inch (0.279 cm) and powdered boron nitride (BN) ceramic was placed between the heater wire and the heater wall. The heavy wall was incorporated so the cartridges could be directly immersed in the system fluid with little chance of NaK leaks through the element itself. Therefore, the heater wells, and associated gas gaps used on previous heaters were eliminated. Boron nitride was used because it has a thermal conductivity of about 15 (Btu)(ft)/(hr)(ft^2)(^oF) (26 W/(m)(K)) compared to 1.4 (Btu)(ft)/(hr)(ft^2)(^oF) (2.4 W/(m)(K)) for MgO. It was determined that this change would reduce the temperature drop from heater wire to heater wall to about 70^o F (38 K).

Spacer rods and stay rods were replaced with sealed tubes to conserve weight. NaK flow in this heater was similar to that of compact heater 1. Liquid metal entered the lower plenum, was directed through orifices in a single flow-distribution plate, passed longitudinally through the spaces between the heater elements and the spacer tubes, and exited through the top port.

Heavy-Duty Heater 2

In conjunction with the design of compact heater 2, an alternate heater of low heat-flux density was fabricated. Heavy-duty heater 2 was designed with 12 spare heater elements. A total of 204 heater elements were immersed in the working fluid, but only 192 were used during operation, the remainder being spares. The elements were 45 inches (114 cm) long, had a heated length of 43.25 inches (112 cm), a wall thickness of 0.110 inch (0.279 cm), and a heat-flux density of 34 watts per square inch (5.3 W/cm^2) at 600 kWt. These elements, except for length, were identical to the ones used in compact heater 2. This heater weighed 1200 pounds mass (544 kg) and was constructed of 316 stainless steel.

Figure 8 presents a sectional view of heavy-duty heater 2. The spacing between heater cartridges in the upper bulkhead plate was increased to provide an optimized welding surface. This design also provided trepans, which allowed any inadvertent liquid-metal leakage to flow off the top of the heater, rather than to accumulate and short heater-element leads. Because of the increased spacing between cartridges and to simplify fabrication, the NaK flow pattern was changed; spacer rods were eliminated; and baffles were used to direct the flow. System fluid entered the bottom of this heater, passed in crossflow in a serpentine manner over the heating elements, and exited through the upper port. The heating cartridges were again directly immersed in the system fluid.

METHOD OF DESIGN CALCULATION

Heater component design was divided into three areas: heat-transfer analysis, pressure drop calculations, and stress analysis. Calculations are presented in a general form and they apply to all electric heaters.

Heat-Transfer Analysis

The heater size was selected either to approximate the reactor (small size) or to operate at a low heat-flux density (large size). Heater-cartridge diameter and spacing were assumed. A configuration of spacer rods or baffles was then selected to provide a channeled path for the fluid. The design heater length was altered to give the required total heat-transfer area. A heater-wire temperature check was then made to determine if the maximum heater-wire operating temperature was below 1600° F (1143 K).

In order to determine the required heat-transfer area, the heat-transfer coefficient h of the NaK fluid must be obtained and then substituted in the formula:

$$Q_{reqd} = hA\,\Delta T_{lm} \tag{1}$$

One method of determining h for parallel flow of liquid metal through a tube bundle is presented in Dwyer and Tu's work published in reference 5. A similar calculation to determine the local heat-transfer coefficient for crossflow of liquid metal through a rod bundle is presented in reference 6.

However, for these heaters, a conservative h was estimated (1000 Btu/(hr)(ft^2)($^{\circ}$F) or 5681 W/(m^2)(K)) from data presented in reference 7. The log mean temperature difference ΔT_{lm} was obtained for equation (1) using approximate heater-cartridge temperature data obtained from the manufacturer and the desired inlet and discharge NaK temperatures. The required energy to heat the system fluid from about 1100° F (865 K) to 1300° F (977 K) was obtained using the following formula:

$$Q_{reqd} = Mc_p \Delta T \tag{2}$$

Substitution of all these values into equation (1) will yield a conservative estimate of the required heat-transfer area.

A heater-wire temperature check was then made using data from reference 4. Knowing the maximum heat-flux density of the heater cartridges and the approximate surrounding system fluid temperature, we could obtain the maximum heater-wire operating temperature.

Pressure Drop Analysis

Electric heater pressure drop losses due to flow-distribution orifices, bends, contractions, expansions, and nozzle loss were computed using equations (573) and (596) to (599) of reference 8. The core pressure drop was calculated using friction factor data for a similar heat-exchanger surface configuration presented in reference 9. The basic equation for predicting the core pressure drop of liquid-to-liquid exchangers and for geometries similar to those used in heater component design is given in reference 9 as

$$\Delta P = \frac{v_1 G^2}{2g_c}\left[\underbrace{(K_c + 1 - \sigma^2)}_{\text{Entrance effect}} + \underbrace{2\left(\frac{v_2}{v_1} - 1\right)}_{\text{Flow acceleration}} + \underbrace{f\frac{A}{A_c}\frac{v_m}{v_1}}_{\text{Core friction}} - \underbrace{(1 - \sigma^2 - K_e)\frac{v_2}{v_1}}_{\text{Exit effect}}\right]$$

The flow pattern in heavy-duty heater 2 was normal to the heater elements; therefore, K_c and K_e equal zero in the preceding equation when pressure drop is calculated for this heater.

Total electric heater pressure drop was then computed by summing all the individual losses.

Stress Analysis

A stress analysis was conducted on the heaters for the following operating conditions: a pressure of 50 psig (34 N/cm^2) and a temperature of 1300° F (977 K). The principal stresses investigated were

(1) Cylindrical containment vessel section stress (hoop and meridional)

(2) Stay-rod stress (tension)

(3) Upper-bulkhead-plate stress (ligament bending)
(4) Lower-bulkhead-plate stress (bending)
(5) Inlet and outlet nozzle stress (hoop and bending)
(6) Bulkhead-plate peripheral weld, stay-rod weld, and heater-cartridge weld stress (shear)

Calculations were based on reference 10. Typical stress values for one compact and one heavy-duty heater are listed in table III. Appendix A gives a detailed description of the various heater stress calculations.

INSTRUMENTATION

Temperature

Although all four electric heaters were thoroughly instrumented, only those measurements used in defining component performance are discussed in this report.

All temperatures were measured by Instrument Society of America (ISA) standard calibration K (Chromel-Alumel) sheath-type thermocouples. Compact heater 1 used 18 thermocouples to measure NaK stream temperatures. These thermocouples were inserted into guide tubes and located at the required elevations. The couples were then sealed at the heater lower bulkhead by using compression fittings (fig. 2). A window in each guide tube (fig. 9) allowed the thermocouples to come in direct contact with the system fluid. Six additional couples monitored heater-cartridge outer skin temperature. These thermocouples were inserted in machined slots in the inside diameter of selected heater wells. The readings obtained from these six thermocouples were judged to be average temperatures of the two surfaces they were in contact with.

Heavy-duty heater 1 had a total of 24 thermocouples installed in 12 heaters to monitor heater-sheath inside wall temperature. Figure 5 shows a sectional view of an instrumented heater cartridge used in this heater. The NaK stream temperatures were measured by 27 thermocouples installed as in compact heater 1. The thermocouple external seals (compression fittings) were welded on tubes which extended 12 inches (31 cm) below the heater lower surface. This was done to minimize the seal operating temperature and, therefore, decrease the probability of liquid-metal leaks. All the succeeding heaters incorporated this feature.

The heater cartridge used on compact heater 2 is shown in figure 7. One couple was installed in direct contact with the heater-element inner wall and the second thermocouple was imbedded in the center ceramic. The center couples were assumed to measure the approximate heater-wire temperature. A total of 30 thermocouples were installed in 15 heater cartridges. The NaK stream temperature was measured by 27 thermocouples installed in the same manner as in compact heater 1.

The design of heavy-duty heater 2 was such that 30 thermocouples were placed in 15 heater cartridges, as in compact heater 2. Twenty-six stream couples were installed, as before, in tubes from the heater bottom with windows at the required elevations.

Inlet and outlet heater temperatures were measured by thermocouples spot-welded to the outside diameter of the system piping in close proximity to the heater.

Pressure

The heater-inlet and -discharge NaK static pressures were measured by inductive slack-diaphragm Bourdon-tube pressure transducers. The pressure at the diaphragm was transmitted by a NaK-filled capillary tube to a Bourdon tube located remotely. Movement of the Bourdon tube produced a corresponding mechanical movement in a set of linkages, the linkage movements producing both a mechanical readout and an electrical signal from a linear variable-differential transformer and a solid-state amplifier. The transducers were calibrated over a 0 to 50 psia (0 to 34.5 N/cm^2) range. The accuracy of each pressure transducer measurement was within 1 percent of its range.

Flow

The NaK mass flow rate through the electric heaters was measured by an electromagnetic flowmeter. The flowmeter consists of three main parts: permanent magnet, flow tube, and electrodes. Liquid NaK flowed through the tube and produced an electromagnetic flow proportional to volumetric flow rate. The temperature of the NaK was measured by a thermocouple located on the flow tube. This temperature was required to determine a value of NaK fluid density for converting measured volumetric flow into mass flow rate.

Power

Hall-effect wattmeters were used to measure heater input power. Each individual phase power was measured and then the three phases were totaled and recorded.

Data Recording

Heater data presented in this report were recorded on a computerized digital data recording system (ref. 11). This system was capable of recording both steady-state and transient test system conditions. A cycle of data, containing 400 different instrument inputs, was scanned and recorded by the system in 11.4 seconds. A computer program which calculated steady-state test system parameters was used to obtain the analytical results.

INSTALLATION AND SUPPORT EQUIPMENT

Heater Installation

Figure 10 shows the Lewis SNAP-8 facility with the first heavy-duty heater installed. The heaters were mounted vertically (with the leads on top) and held in position by a three-point suspension system attached to the top of each heater. The suspension system was designed to allow the heaters freedom to swing horizontally (due to thermal expansion), but not to move vertically. Inlet and discharge heater ports were gas tungsten-arc welded to the system piping.

Six inches (15.2 cm) of block-type insulation was used on the heaters. The insulation was composed of calcined diatomaceous silica blended with other insulating materials and bonded with asbestos fiber. At a mean temperature of 700° F (644 K), the thermal conductivity of this insulation was 0.0558 (Btu)(ft)/(hr)(ft^2)($^{\circ}$F) (9.66×10^{-2} W/(m)(K)). The heater upper bulkheads were not insulated, and forced air was used to cool the power leads directly above these bulkheads.

An ignitron controller supplied electrical power to the heaters through three main bus bars. The heater elements were split into three equal groups connected in a delta. The groups were divided into a number of series-parallel circuits (see fig. 11). Two heater elements were connected in a series string. The series string was fused on both ends (in all heaters except compact heater 1). The series strings were then connected to their respective bus bars. This method of connection was incorporated because each heater element was capable of running at a maximum of 220 volts, while the power controller supplied 440 volts.

Ignitron Power Controller

A power controller was required for reactor simulation to vary the actual power into the heaters in response to the power demand signal generated by an analog computer. An ignitron-type controller was chosen because of its inherent high speed of response to control demand signals, and because of its ability to modulate power to complete turnoff.

Ignitron tubes control power by conducting during a portion of each cycle of the 60-hertz voltage sine wave. The tubes are given a current pulse to initiate conduction and then continue to conduct until the voltage wave changes sign. This controller could supply about 700 kWe total three-phase power at 440 volts line to line. See reference 3 for a description of this controller and its use in reactor simulation.

OPERATING PROCEDURE

Prior to operating the heaters, all heater elements were checked with a 500-volt supply to determine their resistance to ground (except compact heater 1). Any element that read below 1 megohm to ground was not connected to the power supply. This condition was usually caused by moisture in the heating element. The remaining heater elements were energized at low voltage (below 100 V), and the heater was slowly brought up to 150° F (338 K). After 5 days, the temperature was increased to 190° F (361 K), and maintained for an additional 5 days. All elements were then rechecked. Any cartridge that measured less than 1 megohm to ground was not used. The heaters were maintained at about 150° F (338 K) from this point until a system startup was initiated. The aforementioned procedure should be followed since failure to do so will result in permanent internal damage to the moisture-containing heater elements.

During the period when the electric heater and the primary loop were brought to a level of rated temperature, power, and flow rate, the voltage supplied to electric heaters was applied very slowly. The internal heater-element temperatures were monitored and power was shut off automatically if the hot-spot temperature exceeded 1600° F (1143 K). A ground detector was used to signal any short to ground. Also, a device was designed to measure unbalance between the three phases.

TEST RESULTS

Compact heaters 1 and 2 ran into operational problems early in their lives. However, these heaters operated long enough to supply meaningful reactor simulation data. On the other hand, heavy-duty heater 1 performed as required during a 1450-hour SNAP-8 system endurance test. Heavy-duty heater 2 also has a successful record of 700 operational hours and is presently installed in the SNAP-8 facility. This heater was used for system startup and shutdown testing, where it accumulated about 10 thermal cycles and 170 power transients.

Test results indicated that all heaters performed as designed from a heat-transfer standpoint. During normal operation (when all heater elements were functioning), heater-wire temperatures never exceeded the 1600° F (1143 K) maximum limit for any heater. Heater-element overheating occurred only after another type of failure disabled a large percentage of the cartridges in one heater.

Figure 12 presents heater-element hot-spot temperatures as a function of primary-loop NaK mass flow rate. The figure indicates that, in the range tested, the hot-spot temperatures did not vary greatly with changes in NaK flow. What is important is the difference in temperature levels from heater to heater. The high heat-flux density heaters (compact heaters 1 and 2) ran at higher heater-wire temperatures. When the heater-element ceramic insulator was changed and the heater wells and airgaps were eliminated, the wire operating temperature dropped (compact heater 1 compared to compact heater 2). When the flow pattern was changed, as in heavy-duty heater 2 compared to heavy-duty heater 1, more efficient heat transfer resulted and wire temperature dropped a few additional degrees.

Figures 13 and 14 present the internal temperature distributions of the compact and heavy-duty heaters at rated conditions of flow and power. Temperatures shown in the heaters are at three elevations: the inlet, middle, and discharge. Shown at each level are the NaK stream temperatures, the heater-cartridge inside-diameter temperatures, and the heater-wire temperatures (compact heater 2 and heavy-duty heater 2). The primary loop NaK fluid temperature rise within the heater can be observed from these figures. It should be noted that the center of the heater discharge end is in all cases the hottest spot in the units. The effect of changing the heater-element ceramic insulator and eliminating heater wells and their associated airgaps is again seen in figures 13 and 14. Taking this data and calculating the average temperature difference from inside the heater elements through to the NaK stream shows that the new heater-element configuration will operate at least 40° F (22 K) below the original design. It should be recalled that the heater-element internal temperatures shown in these figures for compact heater 1 and heavy-duty heater 1 indicate only the wall temperature, not the actual heater-wire temperature. Therefore, the number 1 heaters were running wire temperatures about 50° F (28 K) hotter than those shown in figures 13 and 14. From this information, it can be concluded that heater elements in compact heater 1 (worst case) actually ran close to a calculated operating temperature of 1500° F (1088 K).

Heater pressure drop as a function of NaK mass flow rate is presented in figure 15. At maximum operating flow for any heater, the pressure drop did not exceed 7 psi (4.8 N/cm^2). In all testing performed using these heaters, heater pressure drop was not a limiting factor.

Compact heater 1 had a greater pressure drop than the other heaters. The greater loss can be attributed to the fact that this unit had the smallest open area through its flow-distribution plate. In the design calculations, it was found that most of the heater pressure drop was due to the orifices in these plates. When this heater was designed, it was thought that a relatively large pressure loss was required in order to assure even flow distribution throughout the heater. However, testing indicated that a lower loss provided acceptable flow distribution. Also, there was a system requirement to reduce heater pressure drop in future testing. Therefore, the remaining heaters incorporated larger diameter orifices.

Compact heater 2 and heavy-duty heater 1 had essentially the same pressure drop. Compact heater 2 had about 14 percent greater open area in its distribution plate; however, the core velocity was higher, causing increased frictional pressure drop. The two factors appear to have offset each other, resulting in approximately equal loss for these two heaters. The low-pressure-drop characteristics of these two heaters were considered to be very desirable from a SNAP-8 system viewpoint since the head rise of the primary subsystem pump was limited.

Heavy-duty heater 2 pressure drop data fell between the other heater data. The large number of 180° bends, due to the serpentine flow pattern, contributed significantly to this heater's pressure drop. An increase in open area at the flow baffles would reduce this heater's pressure drop to the pressure drop level of compact heater 2 and heavy-duty heater 1.

Figure 16 shows the heater overall efficiencies for various system mass flow rates. Heater efficiency was defined as the ratio of thermal output $(Mc_p \Delta T)_{NaK}$ to electrical input. To a great extent, heat loss will determine a heater's efficiency. The same type and thickness of insulation was used on all heaters.

Compact heaters 1 and 2 have efficiencies above 90 percent in the normal operating range, above 30 000 pounds mass per hour (3.78 kg/sec). These high efficiencies were expected because the heaters were small and had correspondingly low heat losses. Late in the life of compact heater 1, it was determined that it was advantageous to cool the power leads located on top of the heater. The data presented for compact heater 1 do not reflect this additional heat loss, as it was incorporated on later heaters. The additional cooling is the reason why compact heater 2 efficiency was less than that of compact heater 1 (by about 4 percent) for the same NaK mass flow rate.

The physical size and corresponding large heat-loss area of heavy-duty heaters 1 and 2 caused these heaters to have lower efficiencies than the compact heaters. Heavy-duty heater 2 had an efficiency about 8 percent lower than heavy-duty heater 1 for similar flow rate conditions. This was due primarily to a 6.75-inch (17.2-cm) increase in diameter.

Reactor Simulation

The compact heaters were replaced before simulation testing was completed. Therefore, the two larger heaters had to be used to complete testing. The heavy-duty heaters were approximately three times slower in thermal-dynamic response than the SNAP-8 reactor. However, since reactor transient response is more dependent on nucleonic than on thermal-dynamic characteristics and since nucleonic equations, which describe the nucleonic behavior of the real reactor, were programed in the heater-controlling analog computer, the nucleonic effect tended to override the inaccuracy of the thermal-dynamic simulation (ref. 3). The total simulation, therefore, was generally similar in behavior to the SNAP-8 reactor.

TEST EXPERIENCE AND SPECIAL PROBLEMS

The heaters discussed in this report operated for a total of about 4400 hours. A detailed breakdown of the operational hours for each heater is as follows:

Heater	Operating time, hr	Remarks
Compact heater 1	1300	Operated for 1050 hours for facility shakedown at low power and 250 hours at design conditions
Heavy-duty heater 1	2120	-------------------------
Compact heater 2	300	-------------------------
Heavy-duty heater 2	700	Presently installed in Lewis SNAP-8 system test facility

During these hours of operation, a great deal of experience was obtained. This experience was reflected in a number of design modifications.

The majority of the design problems became evident during the life of compact heater 1. Originally there was a metallic support bar grid on top of this heater (fig. 17). The bars were at times in contact with the power leads. The high temperature on the heater upper surface, in time, adversely affected the lead insulation. Several shorts developed before the situation was discovered and the bars removed. Cooling fans were also incorporated to protect the lead insulation on all heaters.

Heater-element internal arcing and shorting problems also developed. The three main reasons found for these problems were moisture in the heating elements, too high an operating temperature, and too little insulating material between the heater wire and the heater wall. Moisture was removed from later heaters by a slow baking process; special instrumentation was included in the suspected hot regions of later heaters to monitor wire temperature; and all heater elements were X-rayed to locate elements with internal defects.

Internal arcing occurred in compact heater 1. As a result, a hole was burned through the heater-cartridge wall and well. It was then possible for NaK to pass through the hole, into the heater-element core, and out the heater-element top onto the upper bulkhead plate. The liquid metal then shorted every lead with which it came in contact. Arcing damage was minimized in the remaining heaters by fusing the individual heater elements and later by increasing the heater wall thickness. Fusing limited the power available for arcing.

Independent shorting tests were conducted to determine what heater wall thickness would be required to withstand a heater-wire-to-heater-wall short without wall rupture. With deliberate arcing, tests indicated that the 0.110-inch (0.270-cm) heater walls used in the last two heaters would not burn through even when 440 volts were applied. See appendix B for test details.

Compact heater 2 experienced NaK leakage problems through the heater-element gas tungsten-arc weld to the upper bulkhead. A helium mass spectrometer leak check located a number of leaks during fabrication and these leaks were repaired. However, the heater cartridges were positioned so close together in the upper bulkhead plate that approximately 50 percent of the weld beads overlapped. As the heater came up to operating temperature, leaks developed at the overlaps. These temperature-sensitive joints were eliminated by separating the heater elements, as in heavy-duty heater 2. It is recommended that, in future heaters, the heater elements be separated to eliminate weld overlaps, and to make room for the trepans which provide a superior welding surface.

Another welding technique tested, and shown in figure 18, uses an electron beam welder to join the heater cartridges to the upper bulkhead trepans. One-half-inch (1.27-cm) penetration is common with electron beam welding. In comparison, the heaters described in this report had penetrations of about 0.12 inch (0.32 cm). The deeper weld penetrations should be incorporated in future heaters.

One suggested design for a future compact heater incorporating the design experience of the four heaters resembles heavy-duty heater 2, except that the length and number of heater elements would be decreased. The flow baffles would also have to be modified. The design of heavy-duty heater 2 is, however, acceptable for future heavy-duty units. Rigid quality-control standards must be maintained in the fabrication of all future heaters. The heater elements should be inspected thoroughly, and ideally they should be internally free of moisture.

Mercury contamination of the nickel heater leads both inside the cartridges and in the wire bundles was a problem. Mercury spillage from previous work contaminated the test facility. Embrittlement and separation of the power leads at a point about 2 inches (5.1 cm) within the heater elements resulted. Figure 19(a) shows the embrittled area of a nickel lead where separation took place. A magnified cross-sectional view of a lead is presented in figure 19(b). The etched sample indicates the presence of an attacking medium at the grain boundaries. The weakened grain boundaries caused failure through the cross section. To alleviate this problem, more effective mercury cleanup procedures were established and the lead bundles were replaced when contamination was suspected. An additional seal should be incorporated into the lead end of future heater elements to reduce contaminant (mercury, water, etc.) inleakage.

CONCLUDING REMARKS

Four electric heaters were designed to fill the energy requirements of the Lewis SNAP-8 system. The system required primary loop fluid (NaK) to be heated from 1100° F (865 K) to 1300° F (977 K). Compact heater 1 and heavy-duty heater 1 were designed for 34 500 pounds mass per hour (4.34 kg/sec) NaK flow, and compact heater 2 and heavy-duty heater 2 were designed for 45 000 pounds mass per hour (5.66 kg/sec) flow. Although these heaters were designed for the SNAP-8 system, they may be used in many liquid-metal systems over a wide range of temperatures and flows, the only limitation being maintenance of heater-wire temperatures below 1600° F (1143 K).

The compact heaters were designed to physically simulate the SNAP-8 reactor thermal-dynamics, while the heavy-duty heaters were designed primarily to provide a highly reliable heat source. The results obtained from the four heater designs and the associated tests were as follows:

1. Compact heaters 1 and 2 had operational problems early in their lives and had to be replaced prior to the completion of their respective tests. However, most of the design problems became evident with these compact heaters, and as a result the final design of heavy-duty heater 2 was greatly improved. Heavy-duty heaters 1 and 2 were used during most of the testing and were considered successful.

2. The heavy-duty heaters were slower in thermal-dynamic response than the SNAP-8 reactor. However, the total reactor simulation, including the heater-controlling analog computer, was generally similar in behavior to the SNAP-8 reactor.

3. All heaters performed as designed from a heat-transfer standpoint. During normal operation, heater-wire temperature never exceeded 1600° F (1143 K). Overheating occurred only after another type of heater failure disabled a large percentage of the heater cartridges.

4. The compact heaters, due to their required high heat-flux density, operated closer to the maximum operational internal heater-element temperature of 1600° F (1143 K) than the heavy-duty heaters.

5. A drop in heater-wire operating temperature resulted from a change in heater-element ceramic insulator and the elimination of heater wells and their associated airgaps.

6. Compact heaters had greater efficiencies than the heavy-duty heaters due to their

small size and lower heat loss.

7. The pressure drop associated with a given heater was within system limitations and did not exceed 7 psi (4.8 N/cm^2) at rated NaK flow conditions.

8. Heater-element internal arcing and shorting problems were limited by removing moisture accumulated in the heater cartridges by a slow baking process, by including additional thermocouples inside heater cartridges to be installed in hot regions of the heater so high wire temperatures could be monitored and prevented, and by X-raying the heater cartridges prior to assembly to locate elements with internal defects.

9. System fluid leaks through the heater-element welds to the upper bulkhead were eliminated by separating the heater elements, by designing trepans in the upper bulkhead plate as in heavy-duty heater 2, and by incorporating rigid leak-check procedures. The heater-cartridge arrangement used in the first three heaters frequently had seal welds that overlapped and leaked at operating temperature. It is recommended that future heaters be designed similar to heavy-duty heater 2, and utilize electron beam welding (in the upper bulkhead plate) because of its excellent penetration characteristics.

10. Operational experience dictated that fans be used to cool electrical leads on top of the heaters.

11. Mercury contamination of the nickel heater leads both inside the cartridges and in the wire bundles can be alleviated by using effective mercury cleanup procedures, by replacing lead bundles when contamination is suspected, and by incorporating an additional seal in the lead end of future heater elements to reduce contamination inleakage.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 10, 1970,
120-27.

APPENDIX A

STRESS ANALYSIS

A stress analysis was conducted on the electric heaters for the following operating conditions: a pressure of 50 psig (34 N/cm^2) and a temperature of 1300° F (977 K). The calculations were based on formulas from reference 10; a typical set of stress values for one compact heater and one heavy-duty heater are listed in table III. The principal stresses investigated are described in the following paragraphs:

The cylindrical containment vessel stresses were calculated by using the classical hoop- and meridional-stress formulas.

Stay-rod axial stress was calculated using the 50-psig (34-N/cm^2) pressure loading. The resistance of the bulkhead plates was neglected in these tension calculations; therefore, the stresses listed in table III are a maximum.

Upper-bulkhead-plate ligament bending stresses were calculated by using loaded-beam theory. The end supports of the beams were the stay rods and the containment vessel edge. The ligaments from the center stay rod out to the six adjacent rods (in the hexagonal pattern) were considered to be loaded beams and to be supporting the load in this center area. The ligaments from the six stay rods out to the containment vessel edge supported the remaining load. The sheath material of the heater cartridges was considered to be reinforcing the ligament members. According to reference 12, credit may be taken for the staying action of the tubes (the heater cartridges or heater wells were welded in the perforated upper bulkhead plate). Two average stresses were calculated for the plate: the ligament bending stress from the center stay rod to the six adjacent rods, and the ligament bending stress from the six stay rods outward to the containment vessel edge.

The lower-bulkhead-plate bending stress was calculated by using the formulas for simply supported circular flat plates. The plate was considered to be uniformly loaded. Even though the plate is welded to the shell edge, giving a somewhat rigid support, reference 13 states that a plate made of ductile material will yield locally at the support edge, forfeiting some of the restraint from a completely fixed edge. The actual strength of such a plate is somewhere between the strength of a simply supported edge and that of a plate with an ideally fixed edge. Credit was taken for the restraint of the stay rods in the calculations. The total strain or elongation of the rods was considered as allowing the plate to deflect an amount equal to this elongation. The stress was calculated based on this deflection.

The triangular flat surfaces of the transition section of the nozzles were considered as a triangular plate with a uniform load supported on all sides (the half-circle pipe section that makes up the sides of a nozzle provides restraint in a direction normal to the flat surface edges. The hoop stresses associated with the inlet and outlet transition sections were calculated by using the standard hoop-stress formula for cylinders.

The bulkhead-end-plate, stay-rod, and heater-cartridge (or heater well) peripheral weld shear stresses were calculated by using the load produced by the 50-psig (34-N/cm^2) pressure. In the case of the compact heaters, the upper and lower plates were welded to the shell with a 0.25-inch (0.63-cm) corner fillet weld. In the case of the heavy-duty heaters, a 0.31-inch (0.79-cm) "U" weld was used in the attachment of the upper plate to the shell and a 0.37-inch (0.94-cm) corner fillet weld was used for the lower plate. Where the corner fillet welds were used only, the throat area of the weld was considered in the stress calculations.

In the case of the stay-rod weld shear stress, the listed value is an average for the seven stay rods. They were considered as accepting the complete load from the 50-psig (34-N/cm^2) pressure. The shear stress on the heater-cartridge (or heater well) weld to the bulkhead plate was calculated based on the 50-psig (34-N/cm^2) load acting on the cartridge-free end.

Data from reference 14 show type 316 stainless steel to have stress-rupture values of 17 000 psi (11 730 N/cm^2) at 1300° F (978 K) for 1000 hours and 10 000 psi (6894 N/cm^2) for 10 000 hours. It also has a 1 percent creep strength of 7900 psi (5460 N/cm^2) in 10 000 hours (ref. 15).

In comparing the stress values of the different parts of the heaters in table III with the rupture strength of type 316 stainless steel, no problem should be encountered in electric heater operation. The normal mode of loading the heater is somewhat cyclic. Creep-rupture time under cyclic loading is much longer than for monotonic loading (ref. 16). Two of the stresses in the compact heater, namely the upper-bulkhead-plate ligament bending stress (7620 psi or 5260 N/cm^2) and the stay-rod weld shear stress (7800 psi or 5400 N/cm^2) are very close to the 1 percent creep strength of 7900 psi (5460 N/cm^2) for 10 000 hours. Therefore, if heater design life was increased to 10 000 to 20 000 hours, it would be desirable to lower the two aforementioned stresses by increasing the bulkhead plate thickness and by increasing the size of the stay-rod weld.

APPENDIX B

TEST DETAILS

Shorting tests were conducted at voltage potentials of 220 and 440 volts to determine what heater wall thickness would be required to withstand a heater-wire-to-heater-wall short without wall rupture. In both cases, 25-ampere fuses were placed in series with the test specimens. Simulated heater wall thicknesses of 0.030, 0.060, and 0.090 inch (0.076, 0.152, and 0.229 cm) were tested at 220 volts. One wall thickness, 0.090 inch (0.229 cm), was tested at 440 volts.

A portion of the heater wall of an actual heater element was removed, exposing the heater wire (fig. 20). A sample "heater wall" (fig. 21) was then remotely brought into contact with the heater wire. The resulting penetration in the test sample wall was measured. Listed in the following table are the samples tested and the penetrations associated with the applied voltages.

Sample thickness		Applied voltage, V	Penetration	
in.	cm		in.	cm
0.030	0.076	220	0.020	0.051
.060	.152	220	.015	.038
.090	.229	220	.010	.025
.090	.229	440	.020	.051

Based on these preliminary tests, it was recommended that a minimum of 0.090-inch- (0.229-cm-) thick heater-element wall be used in conjunction with fuses on each electrical supply line. This recommended wall thickness does have a sizable safety factor. As a result, a small penalty must be paid in heater wall thermal conductivity. However, the elimination of blow holes in the heater walls and their associated NaK leaks will significantly affect the reliability of future heaters.

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TABLE I. - SNAP-8 DEVELOPMENT-REACTOR CHARACTERISTICS

Core outside diameter, in. (cm)	9.4 (24)
Core length, in. (cm)	17.3 (43.9)
Core weight, lbm (kg)	350 (159)
Total reactor weight (with controls), lbm (kg)	700 (318)
Design power capacity, kWt	600
Total fuel elements	211
Heat-flux density, W/in.^{2} (W/cm^2):	
At 350 kWt	61 (9.5)
At 600 kWt	105 (16.2)
Fuel-element diameter, in. (cm)	0.56 (1.4)
Fuel-element length, in. (cm)	17.3 (44.0)
Maximum reactor NaK outlet temperature, ^{o}F (K)	1300 (978)
Design pressure drop, psi (N/cm^2)	4.6 (3.2)

TABLE II. - CHARACTERISTICS OF HEATERS TESTED

	Compact heater		Heavy-duty heater	
	1	2	1	2
Outside diameter, in. (cm)	12.0 (30.5), flat to flat	12.0 (30.5)	14.0 (35.6)	20.75 (52.7)
Length, in. (cm)	25.0 (63.5)	22.5 (57.1)	44.0 (112)	45.0 (114)
Weight, lbm (kg)	600 (270)	380 (172)	1250 (567)	1200 (544)
Maximum power capacity, kWe	516	675	552	800
Thermocouple in NaK stream	18	27	27	26
Total heater cartridges	162	144	192	204
Heater cartridges used	162	144	192	192
Heat-flux density, W/in.^{2} (W/cm^2):				
At 350 kWt	68.0 (10.6)	----------	26.0 (4.03)	----------
At 600 kWt	----------	117.0 (18.25)	----------	34.0 (5.28)
Heater-cartridge dimensions, in. (cm):				
Length	21.0 (53.3)	19.5 (49.5)	40.0 (102)	45.0 (114)
Diameter	0.620 (1.57)	0.745 (1.89)	0.620 (1.57)	0.745 (1.89)
Wall thickness	0.032 (0.081)	0.110 (0.279)	0.032 (0.081)	0.110 (0.279)
Heated length	16.5 (41.9)	16.25 (41.3)	36.7 (93.4)	41.5 (105)
Heater-cartridge ceramic insulator	MgO	BN	MgO	BN
Thermocouples in heating elements	6	30	24	30

TABLE III. - TYPICAL STRESSES ON HEATERS TESTED

	Compact heater 2		Heavy-duty heater 2	
	psi	N/cm^2	psi	N/cm^2
Cylindrical containment vessel section:				
Hoop stress	1200	827	1332	918
Meridional stress	600	414	666	459
Stay-rod axial (tension) stress	3290	2268	7650	5275
Upper-bulkhead-plate ligament bending (average):				
Center stay rod to adjacent rods	2360	1627	2120	1462
Six adjacent rods to vessel edge	7620	5254	4130	2848
Lower-bulkhead-plate bending stress	1792	1236	5320	3668
Nozzles (inlet and outlet):				
Hoop stress	336	232	336	232
Triangular flat surface bending stress	1322	912	1322	912
Bulkhead-plate peripheral weld shear stress:				
Upper plate	853	588	810	559
Lower plate	853	588	943	650
Stay-rod weld shear stress:				
Top	7800	5378	4650	3206
Bottom	2600	1792	4650	3206
Heater-cartridge weld shear stress	212	146	212	146

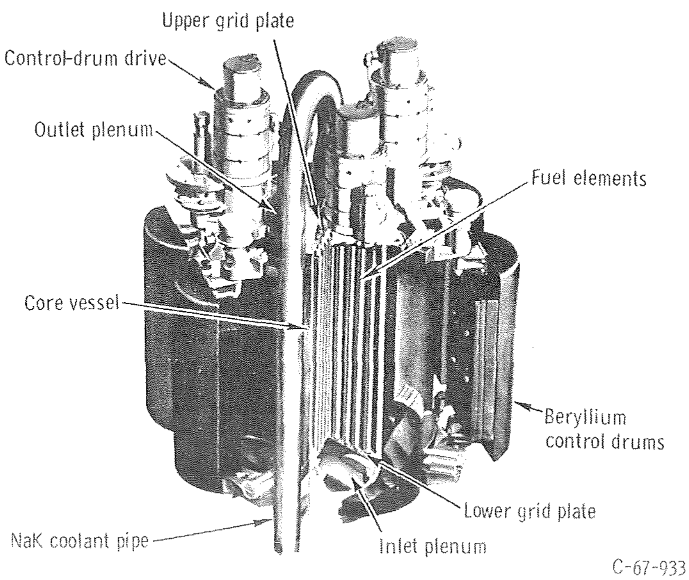


Figure 1. - SNAP-8 development reactor.

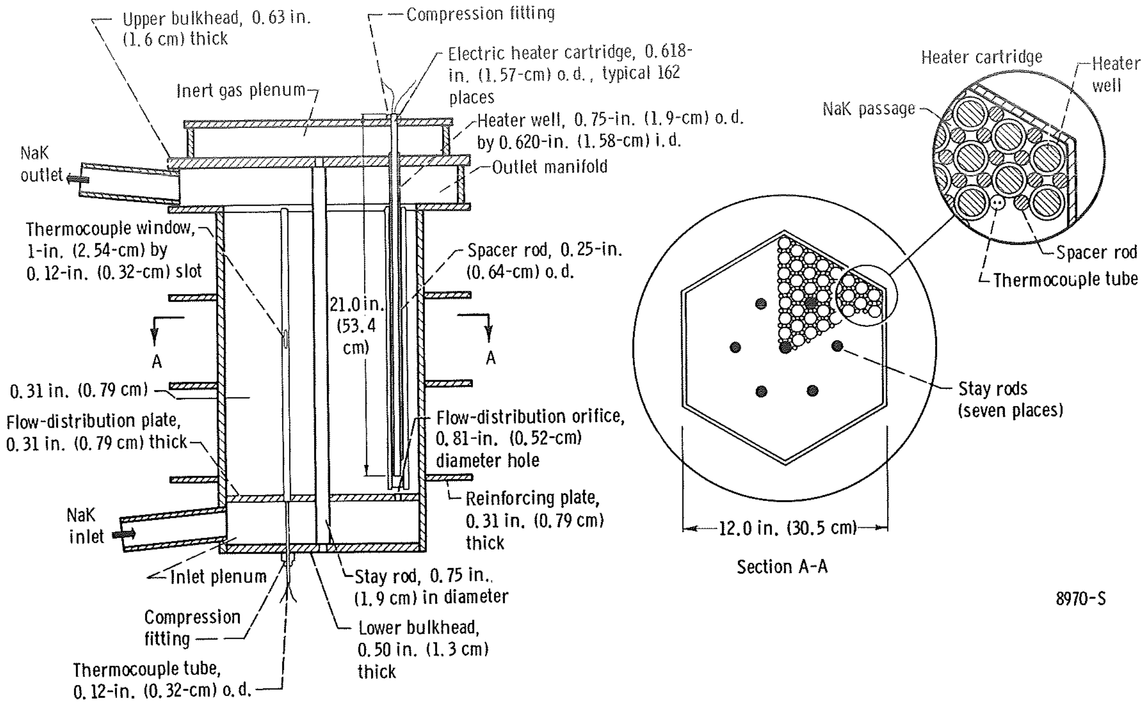


Figure 2. - Compact heater 1.

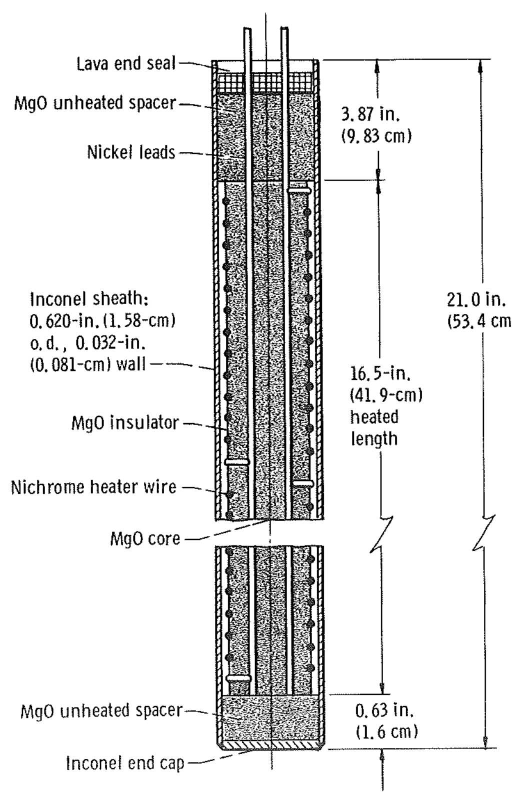


Figure 3. - Heater cartridge used in compact heater.

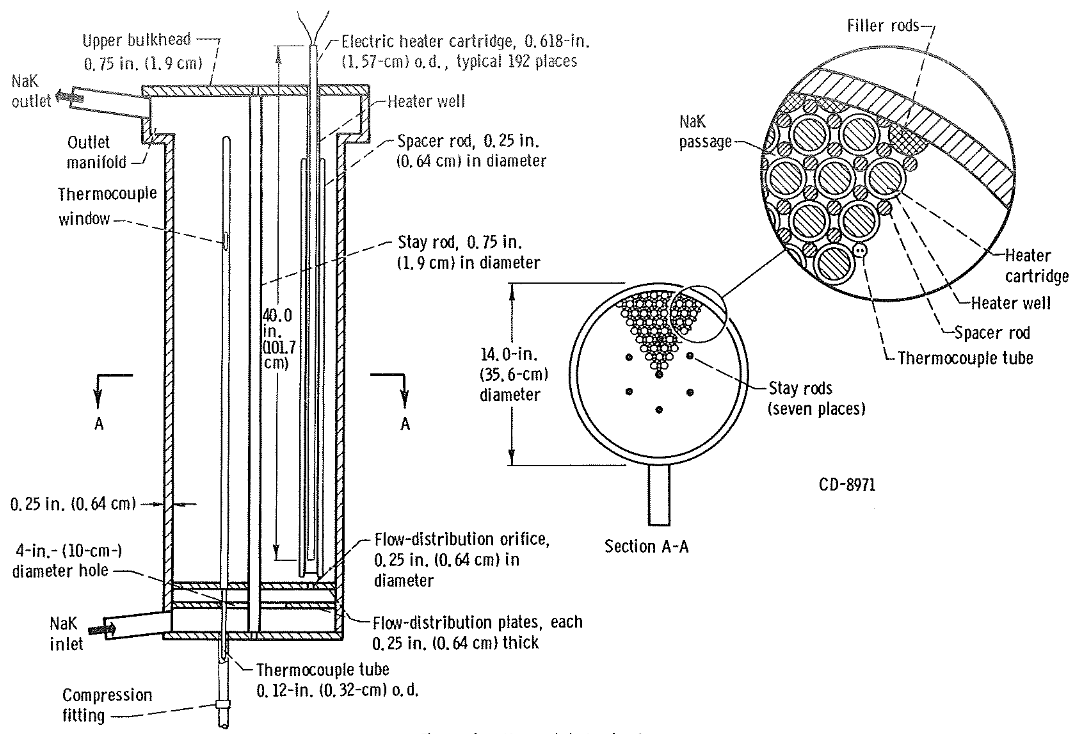


Figure 4. - Heavy-duty heater 1.

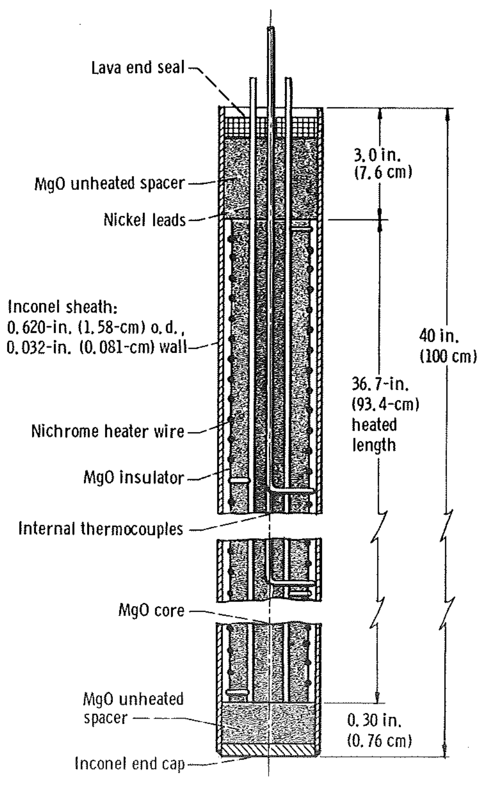


Figure 5. - Heater cartridge used in heavy-duty heater 1.

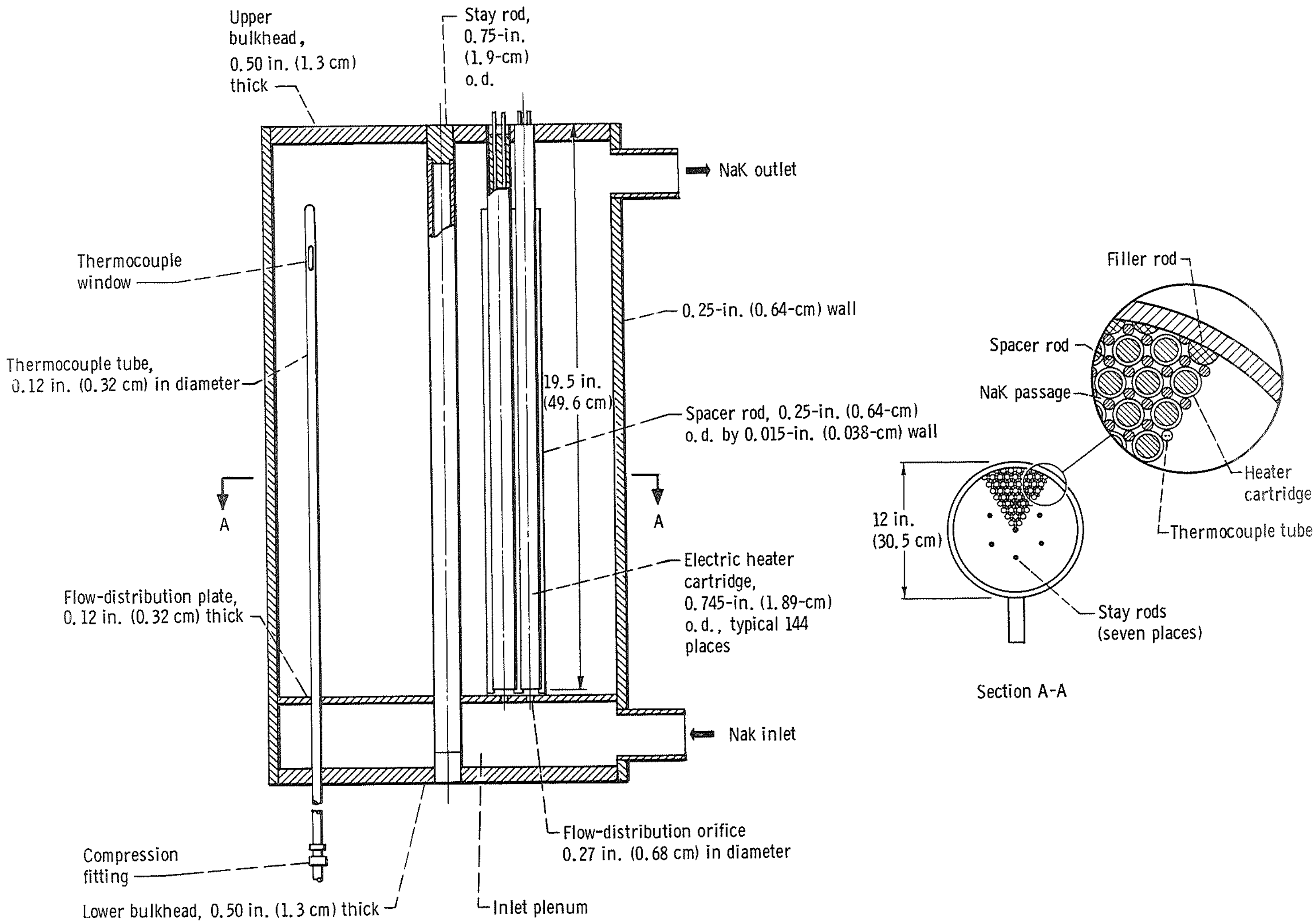


Figure 6. - Compact heater 2.

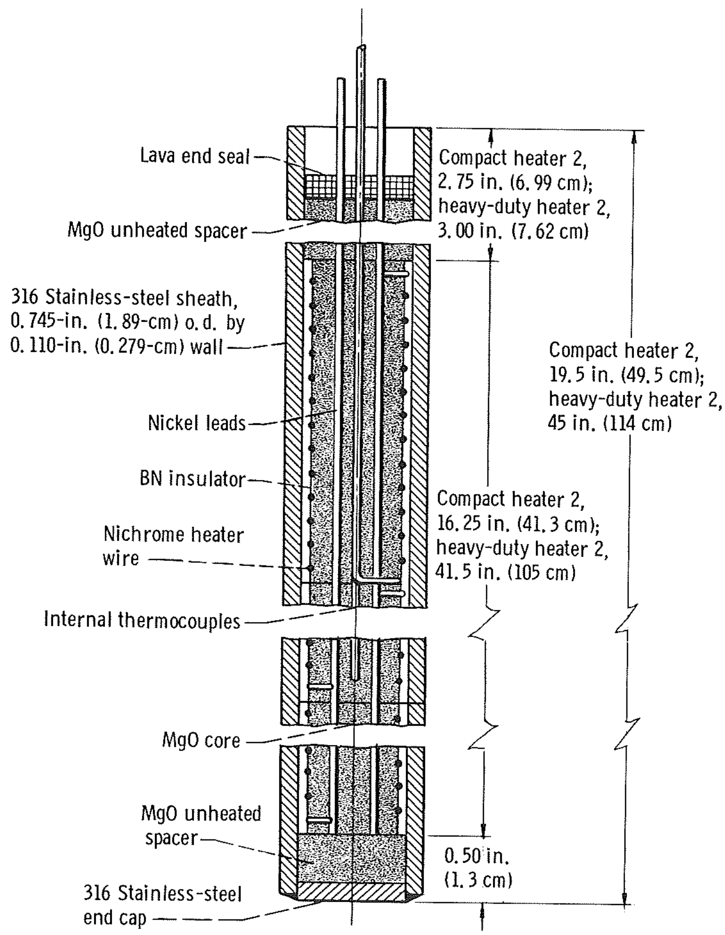


Figure 7. - Heater cartridge used in compact heater 2 and heavy-duty heater 2.

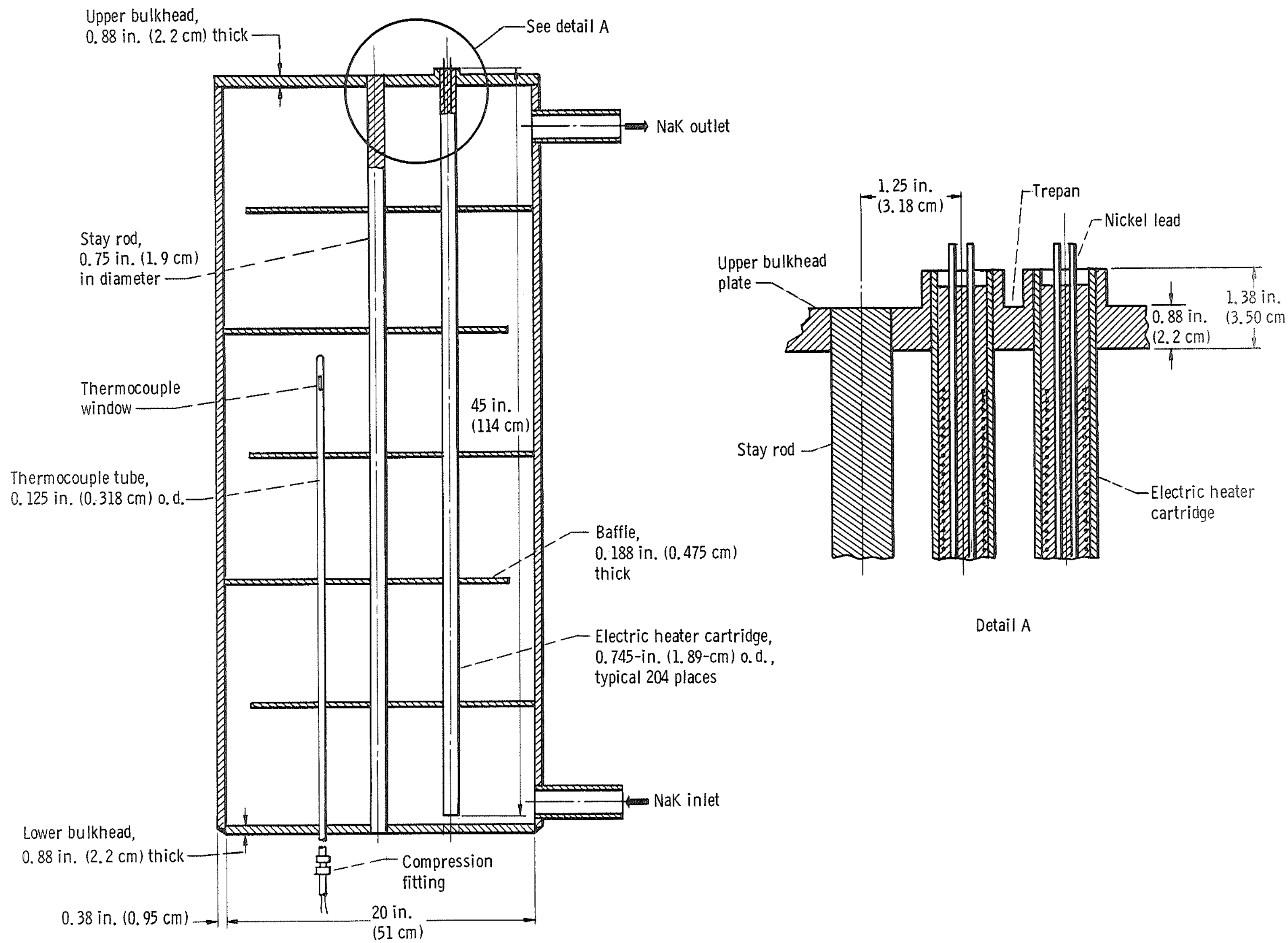


Figure 8. - Heavy-duty heater 2.

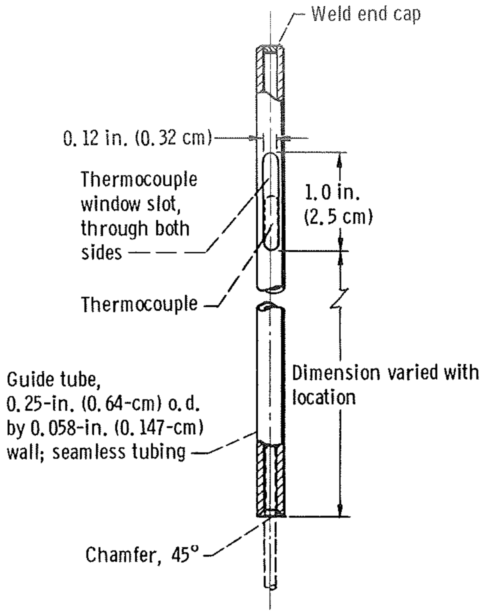


Figure 9. - Thermocouple guide tube and window detail.

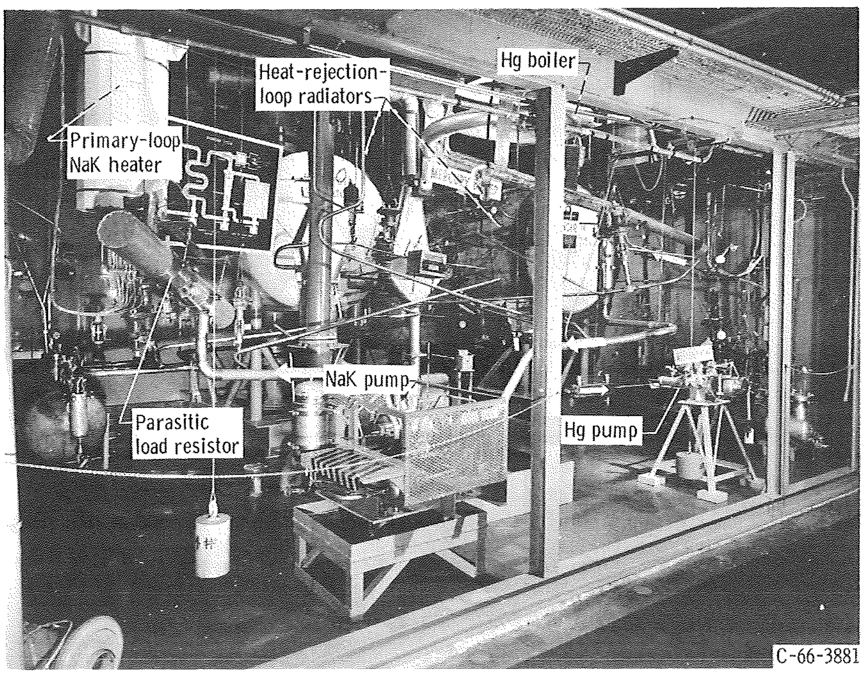


Figure 10. - Lewis SNAP-8 facility.

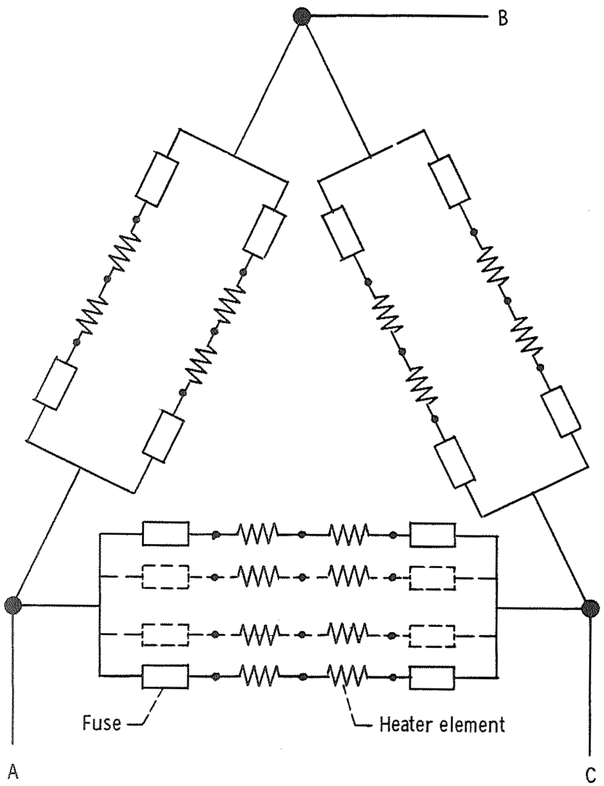


Figure 11. - Schematic of heater-element electrical attachment.

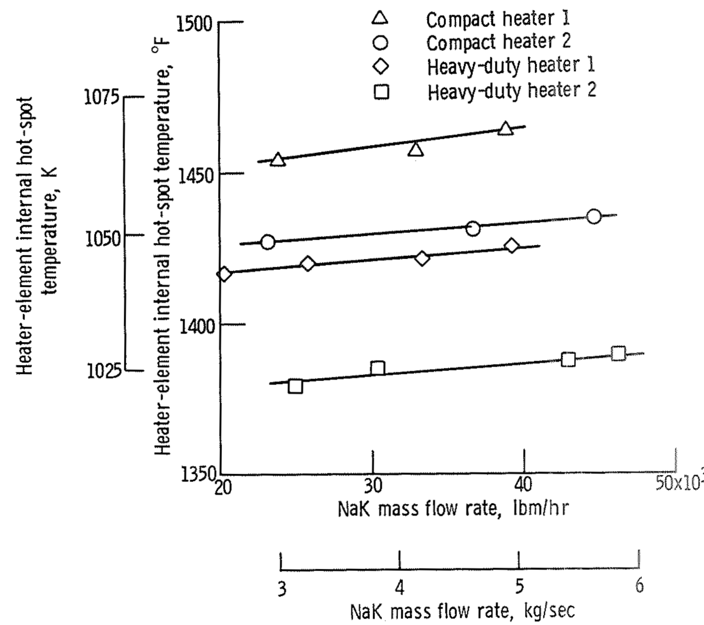
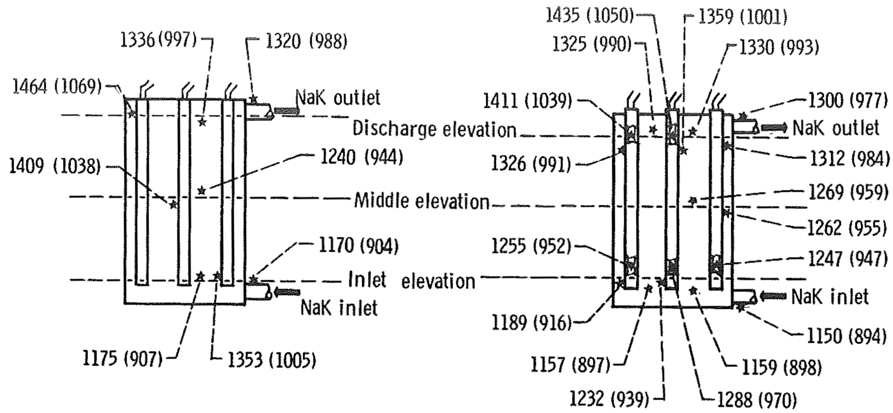


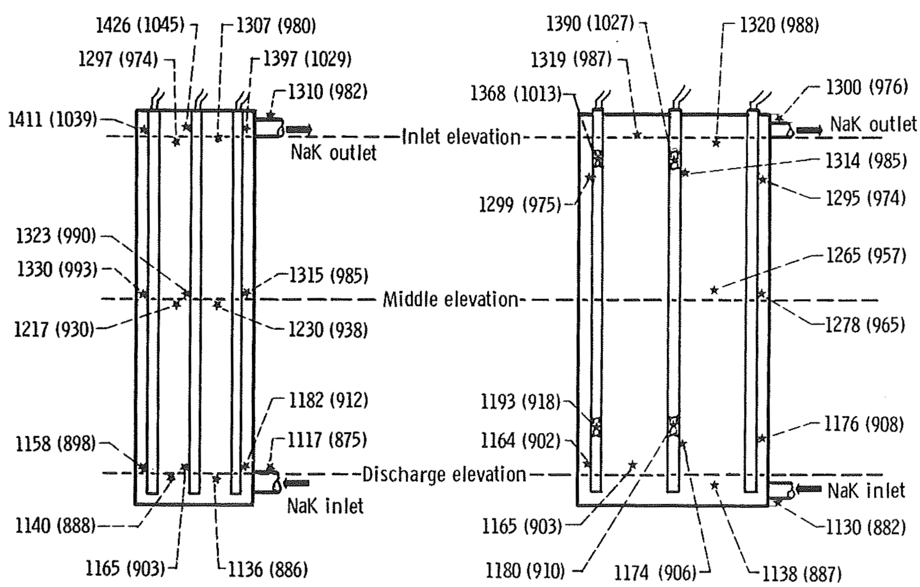
Figure 12. - Effect of NaK flow on heater hot-spot temperature during normal operation. Insulation thickness, 6.0 inches (15.2 cm); NaK outlet temperature, 1300° F (977 K). Temperatures for compact heater 1 and heavy-duty heater 1 were measured at the heater-cartridge wall, not in the cartridge center.



(a) Compact heater 1.

(b) Compact heater 2.

Figure 13. - Temperature distribution in °F(K) - compact heaters.



(a) Heavy-duty heater 1.

(b) Heavy-duty heater 2.

Figure 14. - Temperature distribution in °F(K) - heavy-duty heaters.

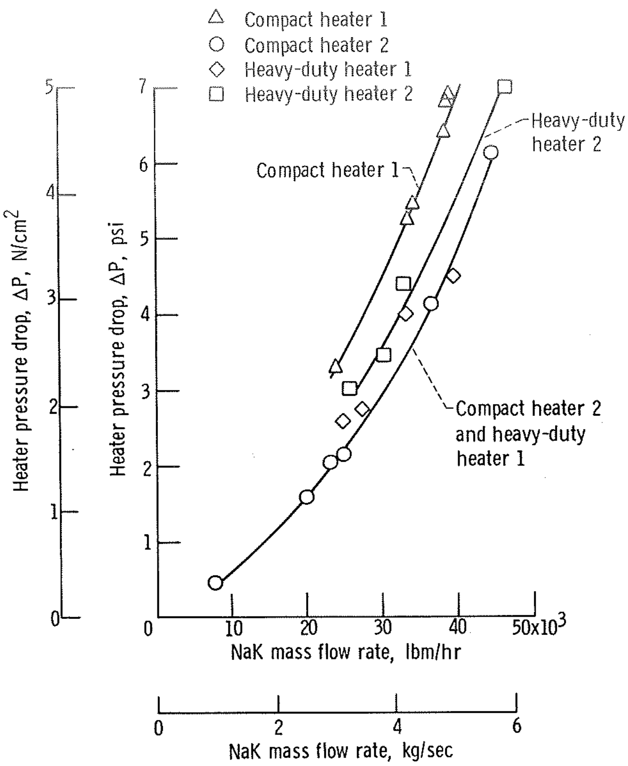


Figure 15. - Effect of NaK flow on heater pressure drop. NaK outlet temperature, 1300° F (977 K).

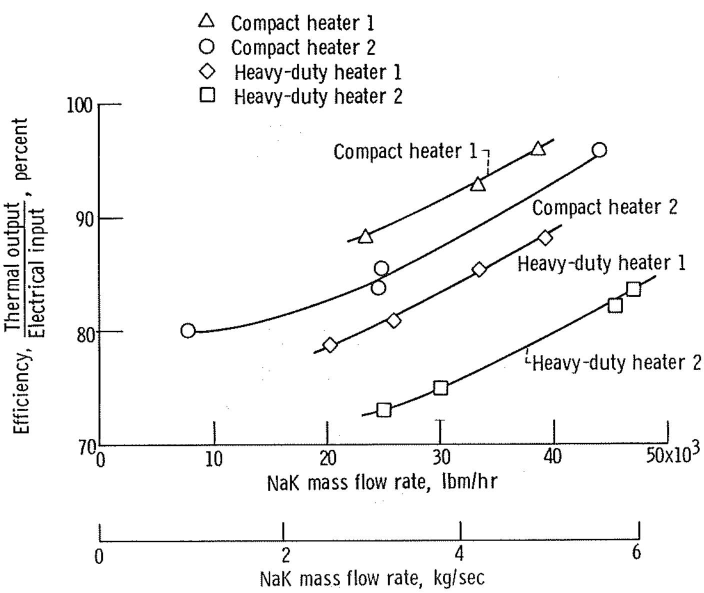


Figure 16. - Heater overall efficiencies. Insulation thickness, 6.0 inches (15.2 cm); forced air on leads (except for compact heater 1); nitrogen environment, 100° F (311 K). NaK outlet temperature, 1300° F (977 K).

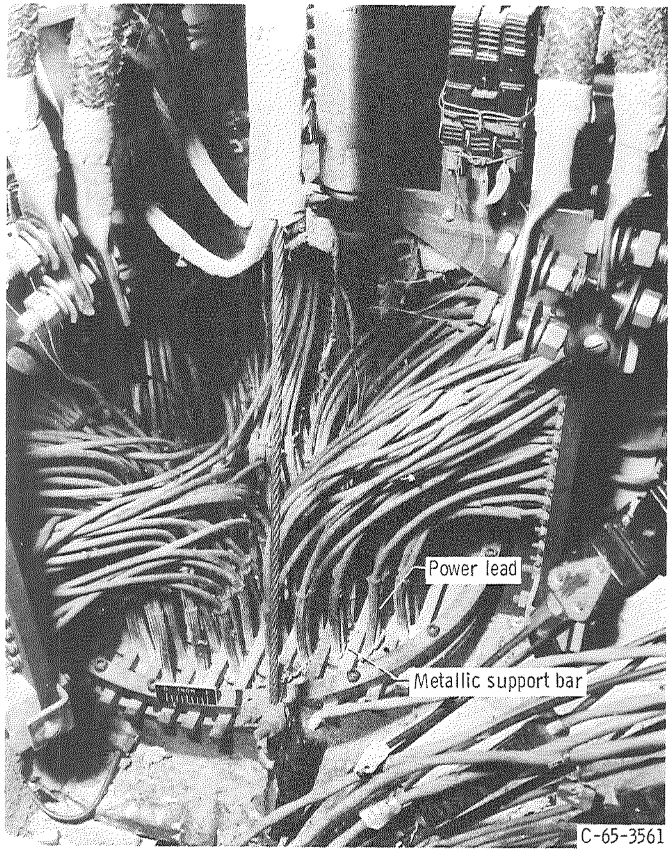


Figure 17. - Upper surface of compact heater 1.

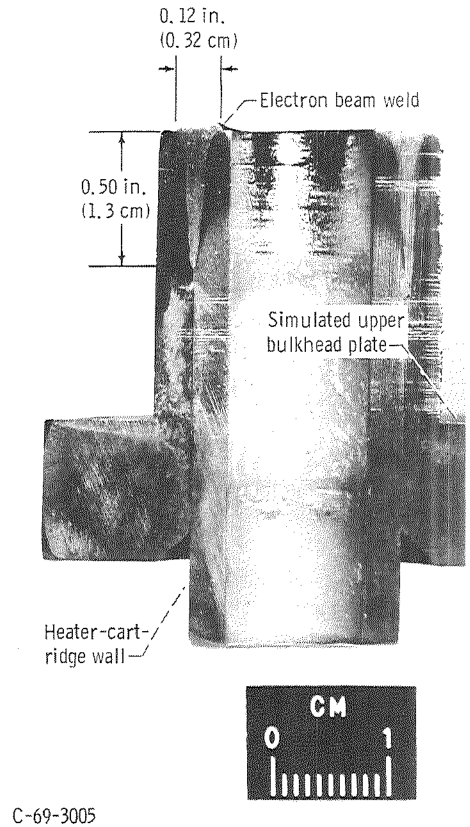
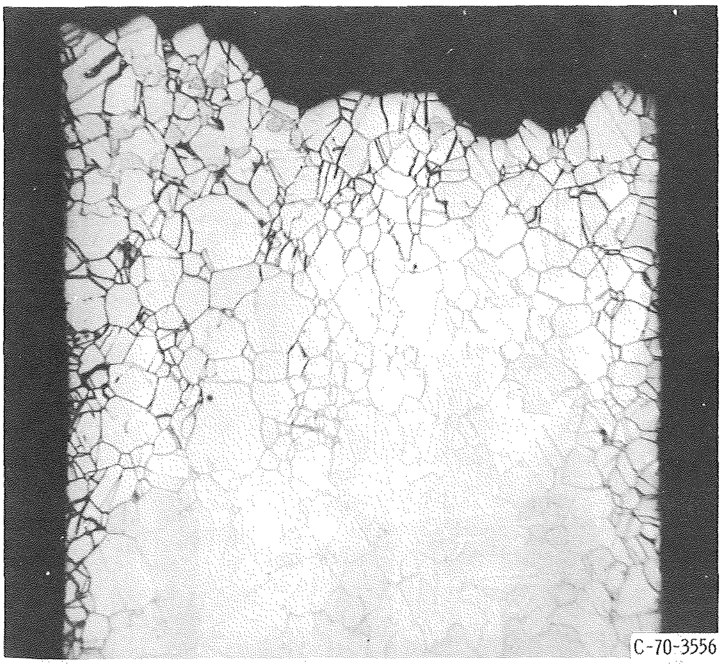


Figure 18. - Sample electron beam weld.

(a) Nickel lead separation caused by mercury contamination.



(b) Magnified cross-sectional view of etched nickel lead grain boundaries.

Figure 19. - Mercury contamination of nickel heater leads.

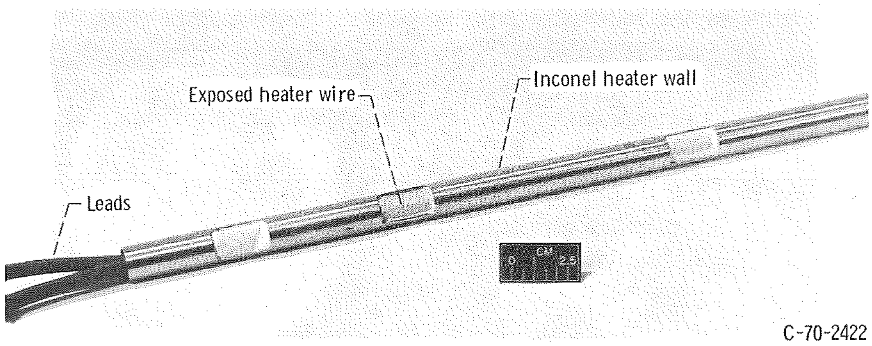


Figure 20. - Sectioned heater element from compact heater 1.

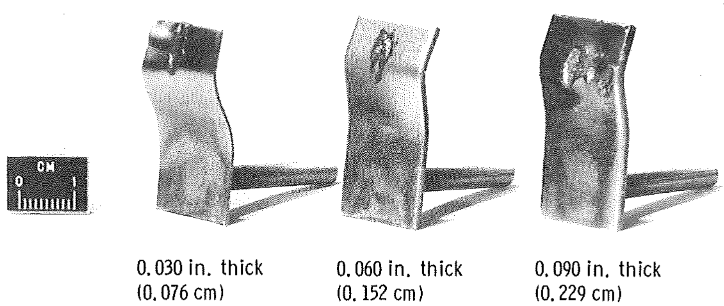


Figure 21. - Simulated heater wall test specimens.

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